

Experimental Validation of High-Performance Hybrid Bridge Piers

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ABSTRACT: An appreciation of the crucial need for a high level of performance from reinforced concrete structures located in seismically active regions has been extensively recognised in the past decade. Appropriate performance-based criteria are essential in ensuring the desired behaviour of structures, especially when a low level of post-earthquake damage is desired.

“Hybrid” jointed ductile connections originally developed for either pre-cast concrete frames and wall systems have been shown to exhibit superior performance complemented with a reduced level of damage and negligible residual deformations of the structural systems. These innovative advanced systems, consisting of relatively simple construction methods (based on post-tensioning techniques), have been recently proposed to be adopted in bridge piers and systems as a viable and highly competitive alternative to traditional monolithic cast-in-place construction.

The present work reports on the experimental validation into the performance of hybrid bridge pier systems in a cantilever configuration (pier to foundation connection). The response of a single hybrid solution, tested under a uni-directional quasi-static testing regime is compared against a monolithic benchmark. Analytical-experimental comparisons are also carried out to validate and further refine simplified procedures, previously presented in literature and available in code-design provisions, to predict the cyclic behaviour of jointed connections.

1 INTRODUCTION

Over the past decade a significant number of structures (bridges and/or buildings) have sustained severe levels of damage, often beyond the repairable condition after a major earthquake event. As a result, a major effort has been recently made to develop innovative structural systems able to limit the damage and related repair costs of the structure after a seismic event.

Based on previous research investigations carried out under the U.S. PRESSS (PREcast Seismic Structural Systems) Program coordinated by the University of California in San Diego (Priestley et al. 1999) for the seismic design of precast frame and wall systems, innovative solutions for seismic-resistant bridge piers have been recently proposed as a viable and promising alternative to traditional monolithic solutions.

In particular, an attractive solution combining unbonded post-tensioning techniques and energy dissipation typically referred to as “hybrid” solutions, have been proposed to be extended to bridge pier systems. A sort of “controlled rocking” mechanism, dictated by the opening of a single gap, is developed at discrete connection interfaces (pier-to-foundation, pier-to-deck), where the inelastic rotational demand is concentrated. Minimum structural damage is guaranteed when compared with the development of plastic hinges, typical of the seismic design of monolithic ductile systems.

Extensive numerical investigations on single cantilever bridge piers and frame bridge systems (Palermo 2004) have highlighted the enhanced performance of jointed hybrid systems, when compared to their monolithic counterparts based on cast-in-situ solutions. Negligible residual displacements are ensured via unbonded post-tension tendons, while an appreciable amount of energy

dissipation (through mild steel, friction or viscous dampers) can be used to control the target maximum displacement, thus ensuring limited damage in the pier and reduced repair costs.

Figure 1 shows an example of two alternative pier systems designed to have the same moment-rotation envelope. While no major differences are observed in terms of maximum drift (slightly greater for the hybrid solution), the monolithic solution suffers significant residual displacements (approximately 30% of the maximum drift in this case) and shows a more asymmetrical dynamic response. The peculiar “flag-shape” hysteresis, typical of a hybrid system, is shown in the moment-rotation behaviour of Figure 1.

The design parameter $\lambda = (M_{pt} + M_N) / M_s$ defines the ratio between self-centring and energy dissipation moment contributions, provided by unbonded post-tensioned tendons plus axial load and mild steel or other dissipation devices, respectively, thus controlling the overall shape of the hysteretic behaviour. Values of λ between 1 and 1.5 guarantee limited displacements and residual drifts, whereas values exceeding 2 can jeopardise the behaviour through a reduction in hysteretic energy dissipation, and greater displacements can occur.

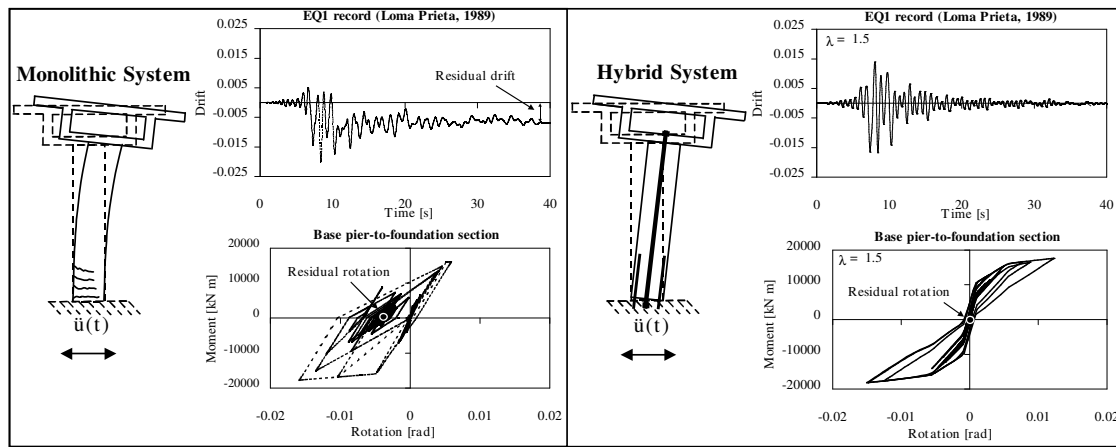


Figure 1. Seismic response of bridge piers with hybrid and monolithic connection (EQ1, Loma Prieta, 1989).

2 OVERVIEW OF THE RESEARCH PROGRAM

An extensive research programme, based on comprehensive numerical and experimental studies on the seismic response of hybrid bridge piers, compared with monolithic benchmark solutions, is on-going at the University of Canterbury. The research consists of three phases. Phase 1 comprises quasi-static and pseudo-dynamic testing on single pier systems, Phase 2 deals with dynamic testing involving the study of impact/contact damping and the adoption of advanced/smart devices, while the final (3rd) phase will deal with various configurations of pier systems including frame piers, coupled with beam caps, and advanced sub-structuring pseudo-dynamic tests to simulate multiple pier supports and non-synchronous motion along with soil-structure interaction.

3 EXPERIMENTAL INVESTIGATIONS ON BRIDGE PIERS WITH CANTILEVER SCHEME: PRELIMINARY RESULTS OF PHASE 1

In this paper, preliminary results of experimental quasi-static cyclic tests on bridge pier specimens with a cantilever scheme are presented. More specifically, the test results on one monolithic and one hybrid solution, with vertical post-tensioned tendons and internal non-prestressed longitudinal reinforcement, will be discussed

3.1 Bridge prototype and specimen design

The prototypes for the monolithic and hybrid bridge systems are illustrated in Figure 2; a bi-cellular box girder deck with total participating mass of 180 tonnes is assumed for both the solutions. The

corresponding monolithic test specimen represents a 1/3 scale reinforced concrete pier designed according to the NZ Concrete Standard (NZS3101:2005 2005a).

The bridge piers were designed according to Displacement-Based Design (Priestley 2003), with a 2% target drift limit corresponding to a design level earthquake (500 year return period). A site PGA of 0.45g was assigned, and then amplified to account for shallow soil conditions (soil category C) according to NZS 1170.5 (SNZ 2004).

It is worth noting, that due to the test set-up characteristics, the hybrid pier was designed to have a slightly lower capacity than the monolithic specimen. With reference to Figure 2, the same axial load demand due to gravity (200kN) was, in fact, assumed between the two systems (hybrid vs. monolithic) and simulated in the test set-up by using vertical tendons. During the experimental tests a constant axial load was maintained in the monolithic pier, while an increasing level of axial load was allowed within the hybrid system due to the actual and expected tendon elongation, typical of such a solution involving a base rotation mechanism. The initial value of axial load (200kN) was thus corresponding, within the hybrid system, to an un-prestressed tendon configuration, which provided a minimum value for the λ ratio (equal to 1.0) and a slightly lower lateral load capacity when compared with the monolithic solution.

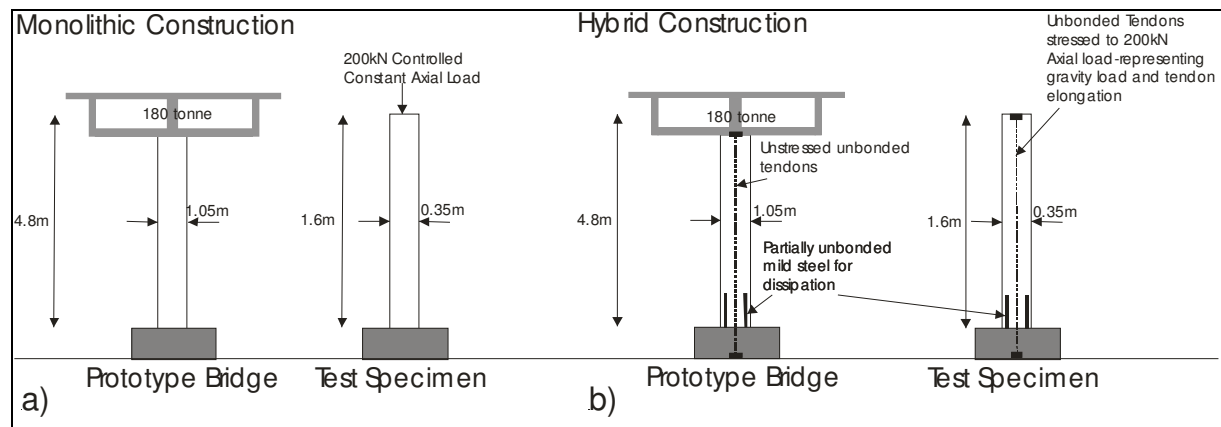


Figure 2. a) Monolithic and b) hybrid bridge pier prototypes and test specimen geometry

3.2 Geometry, reinforcement and material details

Reinforcing details and material properties for both specimens are shown in Figure 3 and Table 1, respectively. Within the monolithic solution, sixteen longitudinal deformed bars (10 mm diameter, Grade 300) were adopted. Within the hybrid specimen, the (internal) dissipaters consisted of four starter bars (16mm diameter, Grade 300) with an unbonded length of 50 mm (Figure 4) successively grouted in the bridge pier. As typical of the theory of hybrid systems, this unbonded length ensured that the strain in the steel would not prematurely rupture compromising the performance of the system.

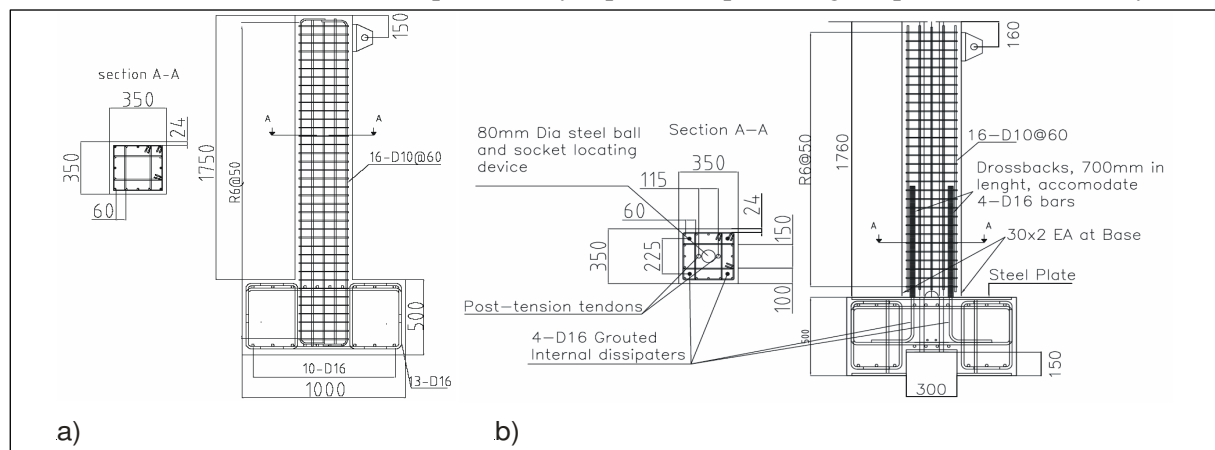


Figure 3. Specimen details a) monolithic solution, b) hybrid solution

Table 1. Material properties

	Hybrid pier	Monolithic pier
f_c (7 days)	40.6 MPa	52.6 MPa
f_c (28 days)	49.5 MPa	66.5 MPa
f_c (Day of test)	54.1 MPa	65.9 MPa
Mild Steel	304 MPa (D16 bar)	317 MPa (D10 bar)
7-wire pre-stressing strand	1600 MPa (yield) 1870 MPa (0.2% proof stress)	-



Figure 4. Hybrid foundation detail indicating starter bars (with unbonded length) and steel locating device

Two unbonded post-tensioned (seven-wire strands) tendons passed through the pier-foundation section (see the ducts of Figure 3) and were anchored on the underside of the foundation (cavity in Figure 3).

3.3 Test set-up and loading regime

The adopted test set-up is shown in Figure 5. The pier-to-foundation specimen (pier 1.6m high, foundation 0.5m x 1.0m x 1.0m) was loaded at the top of the pier, assuming a static cantilever scheme. A series of three cycles of drift, followed by a smaller single cycle, were applied at increasing levels through a horizontal hydraulic actuator, following the “testing protocol for acceptance criteria through tests on innovative jointed pre-cast concrete frame systems” proposed by the ACI T1.1-01 and ACI T1.1R-01 documents (ACI_T1.1R-01 2001).

The axial load was applied to the monolithic bridge pier through a controlled hydraulic jack. As mentioned, the value of 200kN representing the gravity load of the deck, was maintained constant in the monolithic solution. In the hybrid pier specimen the 200kN axial load, simulating the gravity load, was applied through two unbonded post-tensioned tendons. Allowance for tendon elongation was given during the test, as correctly expected from the up-lifting/rocking mechanism in a hybrid system .

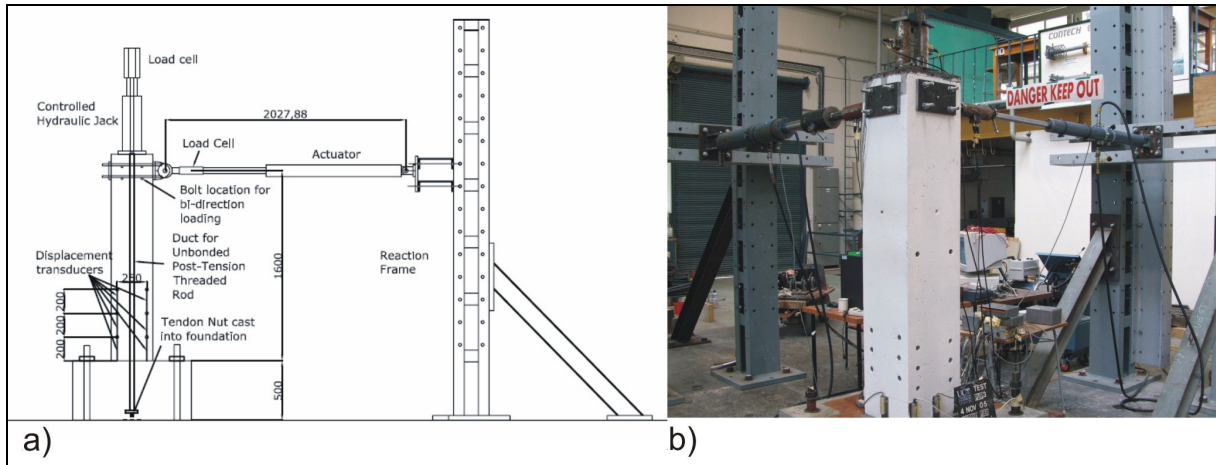


Figure 5. a) Experimental test-rig, b) Photograph of current test set-up

4 EXPERIMENTAL RESULTS AND NUMERICAL VALIDATION

In the following paragraphs, the experimental results of both the hybrid and monolithic solutions will be presented and compared with actual numerical predictions based on a lumped plasticity modelling

approach. The model, implemented in Ruaumoko (Carr, 2005) consisted of elastic beam elements for the bridge piers and inelastic rotational springs with appropriate hysteresis loops located at the critical section interface to represent either the base rotation during the rocking motion in the hybrid systems, or plastic hinges in the case of the monolithic system.

4.1 Monolithic solution

The experimental results (Figure 6) showed, as expected, a fat hysteresis loop typical of a cast-in-place well designed reinforced concrete connection. A sort of pinching behaviour was observed, mainly due to the opening of a single crack at the base of the pier and an increasing degradation of stiffness with drift/lateral displacement. The monotonic numerical prediction matches the experimental envelope curve very well (Figure 6). Furthermore, the cyclic numerical modelling, based on a Takeda hysteresis rule in the plastic hinge region, follows the experimental behaviour with a satisfactory agreement. The limits in the capability of the pinching behaviour are expected due to the simple hysteresis rule adopted. Figure 7 shows the observed damage and performance of the monolithic bridge pier specimen during the testing at drift levels of 1%, 2% and 3%, respectively. The cumulative damage is lumped near the plastic hinge at the base of pier with a clear crack opening at the pier-to-foundation level.

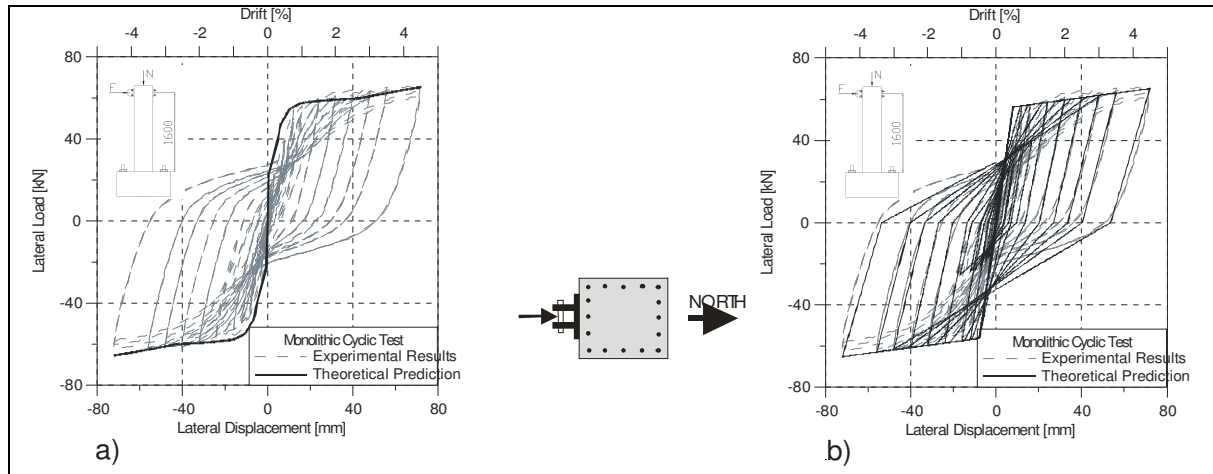


Figure 6. a) Monolithic solution experimental response and b) comparison with analytical predictions

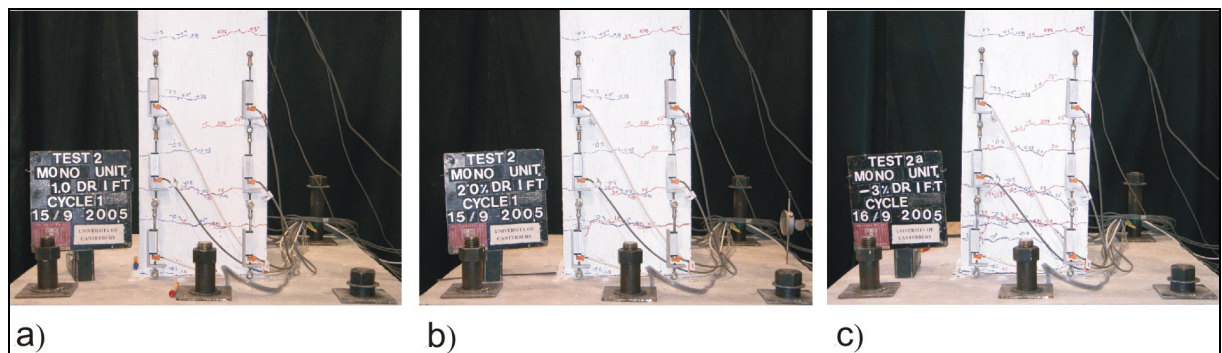


Figure 7. Performance of monolithic pier at a) 1.0% Drift; b) 2.0% Drift; c) 3.0% Drift

4.2 Hybrid solution

Figure 8 shows the response of the hybrid system, indicating a stable experimental “flag-shape” hysteresis (dashed lines), with adequate energy dissipation capacity. However, a fully re-centring capacity was not observed, resulting in some “static” residual displacements. This is mainly due to the relatively low λ ratio chosen during the design phase, as mentioned previously, in order to calibrate the two systems to have the same axial load. Values of λ higher than 1.15 (including steel over-

strength) are in fact suggested in NZS3101:2005 Appendix B, special design provisions (SNZ 2005b). Furthermore, subsequent losses in the tendons due to sliding-movements of the mechanical anchorage and translation sliding of the pier base would accentuate these residual displacements. At a medium-high level of drift, some onset of stiffness degradation was observed, mainly due to deterioration of bond properties between the deformed mild steel bars and the concrete grout injected in the ducts. However the stiffness degradation is less pronounced than that of the monolithic solution shown in Figure 6.

The predicted force-displacement monotonic curve (continuous black line), evaluated using the “Monolithic Beam Analogy” (MBA), (Pampanin et al., 2001), (Palermo 2004), (SNZ, 2005b), overlays the experimental results in Figure 8 (grey dashed line), and further provides an excellent validation of the analytical/modelling procedure. The analytical predictions, based upon the MBA procedure, consist of a moment-rotation section analysis dictated by a single gap opening at the rocking interface (indicative of an infinite curvature). Section strain compatibility is violated at the critical interface of a hybrid section, rendering typical moment-curvature section analyses void. The MBA is derived around the assumption that the displacement between a hybrid specimen and an equivalent monolithic specimen, with identical reinforcing layouts, will follow the same trend deflections, thus allowing a member compatibility condition to be used. A virtual (analogical) concrete strain can be computed, to then allow a full section analysis to be evaluated in terms of Moment vs. Rotation.

Further validation of the adopted analytical model, can be deduced from the tendon behaviour. Figure 8b) illustrates the variation of tendon force versus base rotation, due to a direct elongation of the tendon. The comparison between predictions and experimental results shows a good agreement while the prediction slightly over-estimates the experimental results. As mentioned, some degradation of the tendons’ load occurs during loading in the higher cycles as a result of the sliding movements of the mechanical anchorage and tendon-friction losses. It is worth noting that, even when neglecting such an effect, the global response of the system can be well captured. While the predictions overestimate the experimental tendon force by approximately 3%-5%, the limited moment contribution of the tendon to the overall moment capacity (i.e. 50%) would result in only minor differences (in the order of 1.5%-2.5%) between the prediction and experimental moment vs rotation.

Figure 9 highlights the enhanced performance of the hybrid solution when compared to the monolithic pier (designed with similar moment-rotation capacity), in terms of minimal damage and residual displacements.

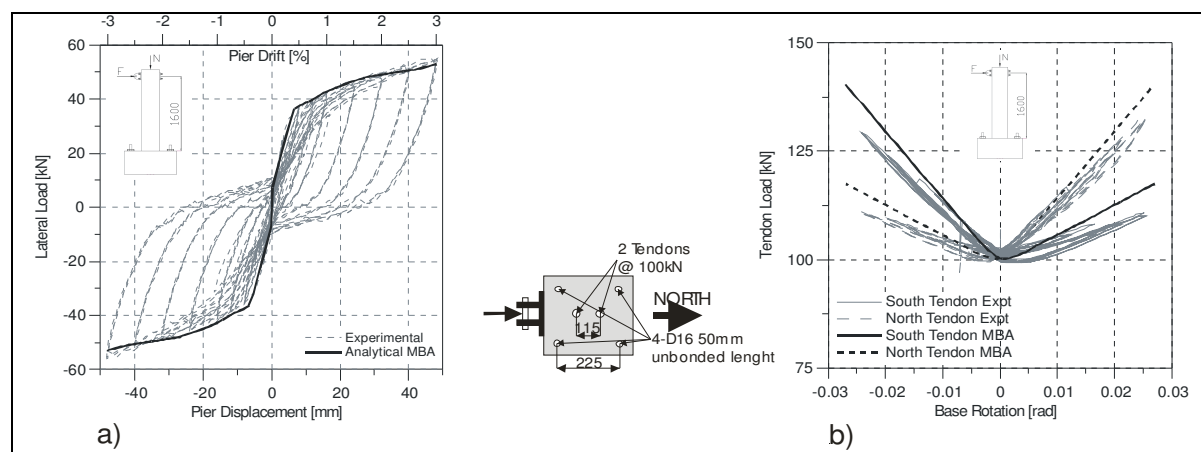


Figure 8. Hybrid pier response and experimental-analytical comparison a) force-displacement hysteresis; b) variation of post-tensioning force

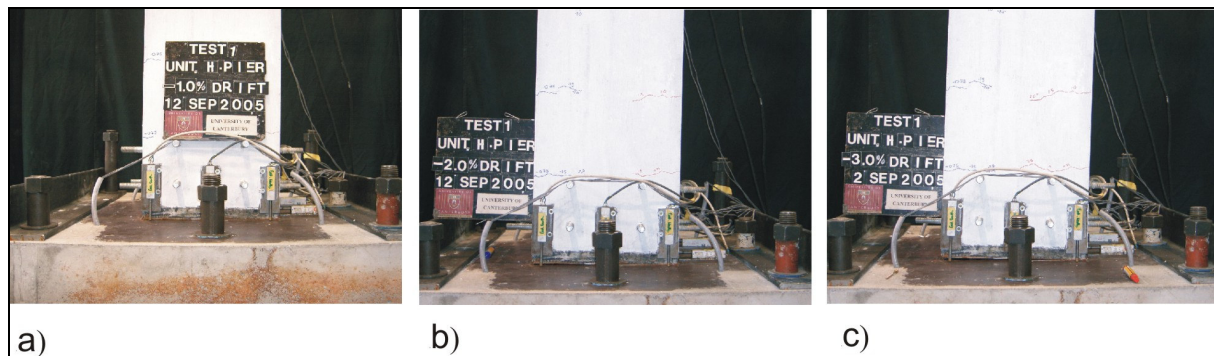


Figure 9. Performance of hybrid solution at increasing level of drift: a) 1.0% Drift, b) 2.0% Drift, c) 3.0% Drift

4.3 Calibration of the lumped-plasticity model

According to the analytical modelling of jointed ductile connections (Pampanin et al. 2001), (Palermo 2004), the idealised “flag-shape” hysteretic moment-rotation can be obtained by a combination of two springs in parallel; a Multi-Linear-Elastic/ re-centring spring and an Elasto-plastic, (or similar) steel/dissipative spring. The two components are assigned independent rotational spring properties (in terms of yield, elastic and post-yield stiffness) as depicted in Figure 10. The pier is then modelled as an elastic beam element (cracked section) rigidly connected to two rotational springs in parallel (of zero length) at the base, as also shown in Figure 10. A multi-linear elastic spring can be assigned to the tendon contribution, while an elasto-plastic bilinear spring can be assigned to the dissipative steel component. Moreover, the dissipative spring could be modelled using a number of alternative representative hysteretic rules such as Ramberg-Osgood (Ramberg and Osgood, 1943) or more-refined to include a Dodd-Restrepo hysteretic behaviour (Dodd and Restrepo-Posado, 1995).

As mentioned, the finite element program, Ruaumoko, was used to provide cyclic push-over comparisons between the experimental results and the analytical two spring model (Figure 10). In this analysis, the multi-linear elastic spring consists of a non-linear point (corresponding to a geometric non-linearity related to a sudden relocation of the neutral axis position), an ultimate point (corresponding to the base rotation at the end of the analysis, not the ultimate section strength) and two intermediate points. A Ramberg-Osgood Hysteresis was assigned to the dissipative spring, indicating a satisfactory backbone curve but overestimating the unloading strength of the system. Secondly, the stiffness degradation is poorly represented by such a hysteresis model. This had a combined effect of slightly over-estimating the energy dissipation of the connection.

It was found that both an Elasto-Plastic and Ramberg-Osgood model provided similar dissipative contributions. Both over-estimate the unloading strength and both are unable to capture the stiffness degradation, mainly due to the bond deterioration within the internal mild steel. Moreover, the adoption of a more refined hysteresis rule, such as Dodd-Restrepo, led to a more pronounced over-estimation of the backbone curve due to the bauschinger effect (intrinsic in the model). In fact, for this hybrid specimen, the grouted internal steel bars would be subjected to significant stiffness degradation due to bond slip thus preventing (or cancelling) any bauschinger effects from occurring; instead a Takeda type loading curve would be more representative.

For this reason it can be suggested that the choice of the most appropriate hysteretic model to represent the energy dissipation contribution should depend on the type of internal or external dissipaters adopted. When an internal (grouted) dissipater is utilised a hysteresis typical of reinforced concrete elements such as Ramberg-Osgood, with some stiffness degradation upon loading, is better suited. On the other hand, when considering external bolted or case-welded dissipation devices, where bond slip would not be present, fatter and more stable hysteresis, typical of steel connections, could be a better alternative such as Elasto-Plastic or better still, Dodd-Restrepo to account for possible Bauschinger effects.

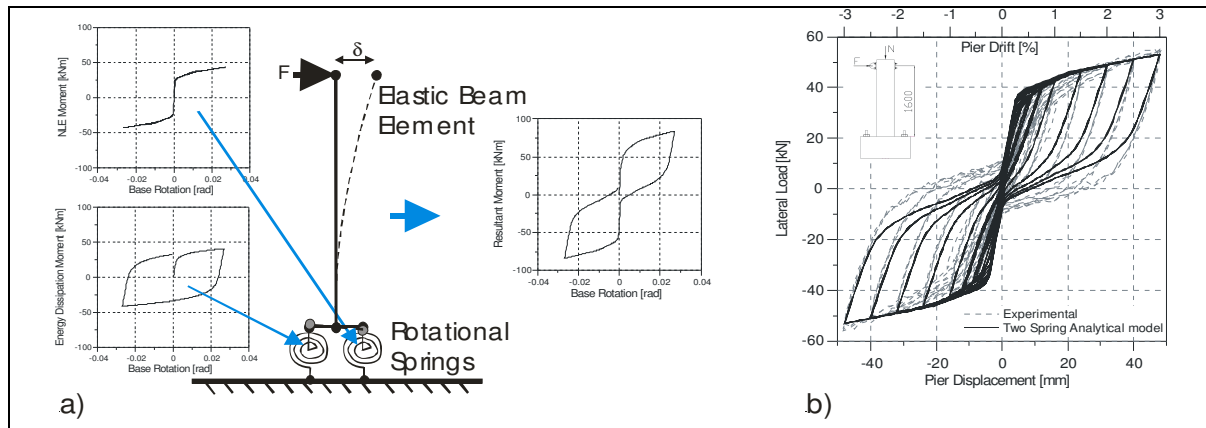


Figure 10. Modelling aspects a) Two springs in parallel concept, b) Experimental-analytical comparison using Ramberg-Osgood hysteretic model

5 CONCLUSIONS

The preliminary experimental results of quasi-static tests on hybrid concrete bridge piers provided encouraging confirmation of the enhanced performance of jointed ductile connections when compared to traditional monolithic solutions. The main advantages of the proposed hybrid solution are: a) the almost complete lack of damage in the structural elements, b) the self-centring properties provided by the unbonded post-tensioned tendons, which guarantees negligible residual/permanent displacements/drift as well as c) a very stable hysteresis behaviour at high levels of ductility without major degradation of stiffness or strength.

The analytical-experimental comparisons, mostly based on pure predictions (i.e. pre-testing numerical simulations) confirmed a very satisfactory accuracy of the simplified modelling proposed and adopted to describe the behaviour of the hybrid connections.

Furthermore, the enhanced seismic performance highlighted the unique potential for future developments and applications in multi-span continuous bridges. Based on these preliminary indications, further investigations for the development of hybrid solutions, adopting different typologies of external dissipation devices (elasto-plastic, friction, viscous), are currently on-going and will be extended to cover alternative lateral bridge pier connections and systems including coupled piers, pier-to-cap and frame-pier systems.

6 ACKNOWLEDGEMENTS

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